

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1632

GUST-TUNNEL TESTS TO DETERMINE INFLUENCE
OF AIRFOIL SECTION CHARACTERISTICS
ON GUST-LOAD FACTORS

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Washington

July 1948

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SUMMARY

Gust-tunnel tests were conducted to determine if gust-load factors for airplanes with low-drag wing sections should be higher than those for airplanes with conventional wing sections. A model having a wing with a low-drag section was used with smooth surfaces and with roughness applied to the leading edge to simulate the flow conditions for a conventional section. The results of the tests indicate that, within the limits of accuracy and precision required for present gust-load calculations, the low-drag and conventional airfoil sections show the same slopes of the lift curve while traversing gusts with gradient distances up to at least 12 chords. For gust-load calculations, it is suggested that, until further information is obtained, the section slope of the lift curve of all airfoils be assumed to have a value of approximately 6.0 per radian and that a simple correction for aspect-ratio effects be applied to obtain the slope of the lift curve for finite wings.

INTRODUCTION

In the determination of the design gust-load factor for an airplane, an important parameter is the slope of the lift curve. Since the slopes of the lift curve in steady-flow conditions for airplanes having low-drag wing sections may be some 10 percent higher than the slopes for airplanes having conventional wing sections, this same difference would be observed in the design gust-load-factor increments as determined on the basis of the present gust-load specifications. The higher design gust loads for low-drag wings have been questioned since, because of the suspected lag in the change of the boundary layer on a wing with a rapid change of angle of attack, the steady-flow slopes of the lift curve for both low-drag and conventional wings may not be applicable in the gust condition. If this is the case, then higher design gust-load factors for airplanes having the low-drag type of airfoil may not be justified.

In order to obtain some information on whether higher gust-load factors for airplanes with low-drag airfoil sections are justified, gust-tunnel tests were conducted on a model with a low-drag wing section. In one test condition, the wing surface of the model was smooth and, in the second test condition, the leading edge of the airfoil was roughened under the assumption that the roughness led to a slope of the lift curve and a condition of flow simulating that for a conventional airfoil. The results of these tests, together with a discussion of their implications, are presented in this paper.

METHOD AND APPARATUS

In order to obtain gust-tunnel test results under the same gust and flying conditions but with two steady-flow slopes of the lift curve for which the difference could be ascribed to a change in the boundary layer, the wing of a skeleton airplane model equipped with a low-drag wing section (fig. 1) was made aerodynamically smooth for a series of flights and then the leading edge was roughened for a second series of flights. The relative acceleration increments imposed on the model for the otherwise similar test conditions are then a measure of the slope of the lift curve that is applicable for unsteady-flow conditions.

The pertinent characteristics of the arbitrary model used in this investigation are given in the following table:

Weight, pounds	11.84
Wing area, square feet	5.44
Wing loading, pounds/square foot	2.18
Span, feet	7
Mean aerodynamic chord, \bar{c} , feet	0.829
Aspect ratio	9
Taper ratio	0.382
Center of gravity, percent \bar{c}	30.5
Wing section	NACA 65 ₃ -418, $a = 1.0$
Lift-curve slope, per radian	
Smooth wing (steady flow)	5.01
Roughened wing (steady flow)	4.18
Theoretical	5.41

A line drawing of the model is shown as figure 2. For tests in the smooth condition, the wing of the model was very carefully finished to obtain an aerodynamically smooth surface. For tests in the rough condition, roughness was added by applying carborundum grains to the leading edge of the wing. The grain sizes used were 0.009-inch-diameter grains from the root section to the 65-percent semispan station and 0.005-inch-diameter grains from the 65-percent station to the wing tip. The roughness was added so that about 10 percent of the area over the forward 7.8 percent of the chord on the upper and lower surfaces was covered by carborundum grains.

The lift-curve slopes shown in the foregoing table were obtained from section data (reference 1) which included the Reynolds number of the gust-tunnel tests. The roughness on the model was within the range of roughness investigated in reference 1. The section data were corrected to finite aspect ratio by means of the methods presented in reference 2. In the case of the roughened wing, the change in the relative grain size with the chord along the span made it necessary to determine a weighted value of section lift-curve slope to which the aspect-ratio corrections could be applied. In addition to the lift-curve slopes based on the wind-tunnel tests of reference 1, the theoretical lift-curve slope for the section was computed according to the methods of reference 3, and the value corrected to finite aspect ratio has been included.

The model was equipped with a small accelerometer that was located in the wing approximately at the center of gravity of the model. Two lights, shown in figure 1, were installed at the wing trailing edge and on the tail of the model for use in the determination of the model speed and pitching motion.

The Langley gust tunnel and associated apparatus used in this investigation are equivalent in principle and in operation to the equipment described in reference 4, although tests of larger models at higher flight speeds are possible with the present equipment. The nearly vertical jet of air provided by the Langley gust tunnel is about 8 by 14 feet in size and can be adjusted to be normal to the flight path of the model. A typical velocity distribution through the jet or gust is shown in figure 3 as the ratio of local gust velocity to the average maximum gust velocity plotted against the distance from the leading edge of the gust tunnel in chord lengths of the model wing. For these particular tests, special screening was placed in the tunnel to reduce the turbulence of the jet to a minimum.

TESTS

The test flights were made for a forward speed of 75 miles per hour through a sharp-edge gust with an average maximum velocity of about 8 feet per second. The Reynolds number of the tests based on the mean aerodynamic chord of the wing was approximately 0.53×10^6 . Eighteen test flights were made, eight of which were made with the wing in the smooth condition and ten of which were made with the leading edge roughened. Flights were made without a gust at intervals during the test flights in order to check the trim and general flight characteristics of the model.

RESULTS

The records were evaluated to determine the forward speed, the gust velocity, and the time history of the acceleration increment obtained for

each flight through the gust. The maximum acceleration increment for each flight was obtained from the time histories and was corrected for minor variations from the specified test conditions on the basis that the acceleration increment is directly proportional to the forward speed and the gust velocity (reference 4). The mean value of the corrected acceleration increments for the smooth and for the rough condition of the model are given in table I. In addition to obtaining the mean value, the test results were utilized together with conventional statistical procedures (reference 5) to obtain the probable error of the mean value shown in table I. The experimental data were also used to obtain the difference between the average acceleration increments for the two test conditions together with an estimate of the probable error of this difference, and the results are included in table I.

For purposes of comparison, the slopes of the lift curve derived from wind-tunnel test data and the method of reference 6 were used to calculate the acceleration increments corresponding to the flight conditions and these values, together with their difference, are included in table I. An estimate of the accuracy of the determination of the lift-curve slopes for the model was used to determine the limits of reliability shown for the calculated results. In addition, the acceleration increment, calculated by using the theoretical lift-curve slope of the wings with the method of reference 6, is included in table I.

DISCUSSION

Inspection of table I shows that there is a difference of only $0.02g \pm 0.02g$ between the averages of the experimental maximum acceleration increments for the two test conditions as compared with a difference of $0.26g \pm 0.08g$ between the values calculated on the basis of the slopes of the lift curve for steady-flow conditions. The comparison of the experimental and calculated differences indicates, therefore, that roughening an airfoil to produce a turbulent boundary layer has no effect on the slope of the lift curve that is applicable in the unsteady-flow conditions of a sharp-edge gust. This result may be extended to the case of conventional airfoils by the reasonable assumption that the flow conditions for a conventional airfoil in the steady state are simulated by those for the roughened low-drag wing. It may therefore be concluded that airfoil-section characteristics have no significant effect on the acceleration increment obtained in the unsteady-flow conditions of a sharp-edge gust.

Since it has been found that, for design purposes, the most probable gust is one with a gradient distance of about 10 chords, the averages of the maximum acceleration increments for the two test conditions were calculated for gusts with gradient distances up to 12 chords by applying the principle of superposition (reference 7) to the test results for the sharp-edge gust. The gradient distance is defined as the distance in the

direction of flight over which the gust velocity varies linearly from zero to a maximum value. The results of these calculations showed only $2\frac{1}{2}$ percent difference between the average values at the gradient distance of 12 chords. On the basis of this simple analysis, then, it is indicated that airfoil-section characteristics have no significant effect on the acceleration increments experienced by an airplane in traversing gusts having gradient distances from 0 to 12 chords. It might be noted that, when the gust-gradient distance becomes great enough for the unsteady-flow conditions to approach those of the steady state, the difference in acceleration increments for the rough and smooth conditions would be expected to approach that indicated by the difference in the steady-flow slopes of the lift curve. From the present tests, however, specification of the gradient distance at which the difference would become noticeable is not possible.

The assumption that a lag in the development of the boundary layer would influence the acceleration increments obtained from the rapid change of angle of attack of an airplane traversing a gust appears to be borne out by the agreement between the acceleration increments obtained for the rough and smooth condition of the model wing (table I). In the unsteady-flow conditions of a gust, it appears that there is no difference in the rate of development of the boundary layer for the two test conditions although, in steady-flow conditions, the difference in the rate is sufficient to cause the difference in slope of the lift curve reflected in the results of the calculation made by use of the steady-flow values (table I). If the finite aspect-ratio slopes of the lift curve given for the various conditions are considered to be accurate, a qualitative estimate of the rate of development of the boundary layer in unsteady-flow conditions can be made by comparison of the experimental and calculated acceleration increments given in table I. It is apparent that if no change occurred in the boundary-layer thickness, the experimental results for both test conditions would be expected to agree with the result calculated by using the theoretical slope of the lift curve for the section. The comparison in table I of the experimental data with calculated values, however, shows that the best agreement between experiment and calculation is obtained with the values calculated by use of the steady-flow slope of the lift curve of the smooth low-drag wing. Some change therefore appears to occur in the thickness of the boundary layer with the rapid change of angle of attack in a gust, but this change is only that small amount associated with steady-flow change in angle of attack of a low-drag type wing section.

In the preceding discussion, it has been stated that airfoil section characteristics appear to have no effect on the acceleration increment obtained from encountering gusts with gradient distances up to 12 chords. This result indicates that the gust-load factor for an airplane incorporating a low-drag wing section should be the same as that for the same

airplane with a conventional wing section. The results also indicate that, for a wing of any section with no fuselage interference, the use of the high section slope of the lift curve of a low-drag wing together with the more accurate methods of correcting to finite aspect ratio would yield the correct acceleration increment due to a gust. Consideration of the basis of the determination of design gust-load factors shows, however, that the level of gust-load factors should remain at the level associated with the steady-flow lift-curve slopes of airplanes with conventional wing sections. In addition, an unpublished analysis of experimental data on many more-or-less conventional airplane models with fuselages indicates that the use of an arbitrary section slope of the lift curve of about 6.0 per radian together with the simplest of corrections to finite aspect ratio would yield the most satisfactory gust-load factors within the limits of present knowledge. For the time being, therefore, it is suggested that, for the calculation of gust-load factors, a section slope of the lift curve of 6.0 per radian be adopted and that the effect of aspect ratio on the slope of the lift curve be accounted for by the simple relation of $\frac{A}{A + 2}$ times the section lift-curve slope where A is the aspect ratio.

CONCLUDING REMARKS

On the basis of gust-tunnel tests of a rough and smooth wing, it is concluded that, within the limits of accuracy and precision required for present gust-load calculations, the low-drag and conventional airfoil sections show the same slopes of the lift curve while traversing gusts with gradient distances up to at least 12 chords. For gust-load calculations, it is suggested that, until further information is obtained, the section slope of the lift curve of all airfoils be assumed to have a value of approximately 6.0 per radian and that a simple correction for aspect-ratio effects be applied to obtain the slope of the lift curve for finite wings.

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Langley Field, Va., February 9, 1948

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TABLE I
COMPARISON OF EXPERIMENTAL AND CALCULATED
ACCELERATION INCREMENTS

Experimental values		Calculated values	
Average maximum acceleration increment, smooth-condition flights	$1.69g \pm 0.02g$	Acceleration increment, smooth condition, based on section data of reference 1	$1.73g \pm 0.08g$
Average maximum acceleration increment, rough-condition flights	$1.67g \pm 0.02g$	Acceleration increment, rough condition, based on section data of reference 1	$1.47g \pm 0.08g$
Difference between average maximum acceleration increments for the two conditions (smooth minus rough)	$0.02g \pm 0.02g$	Difference between acceleration increments for the two conditions (smooth minus rough)	$0.26g \pm 0.08g$
		Acceleration increment for both conditions, based on theoretical lift-curve slope	$1.84g$



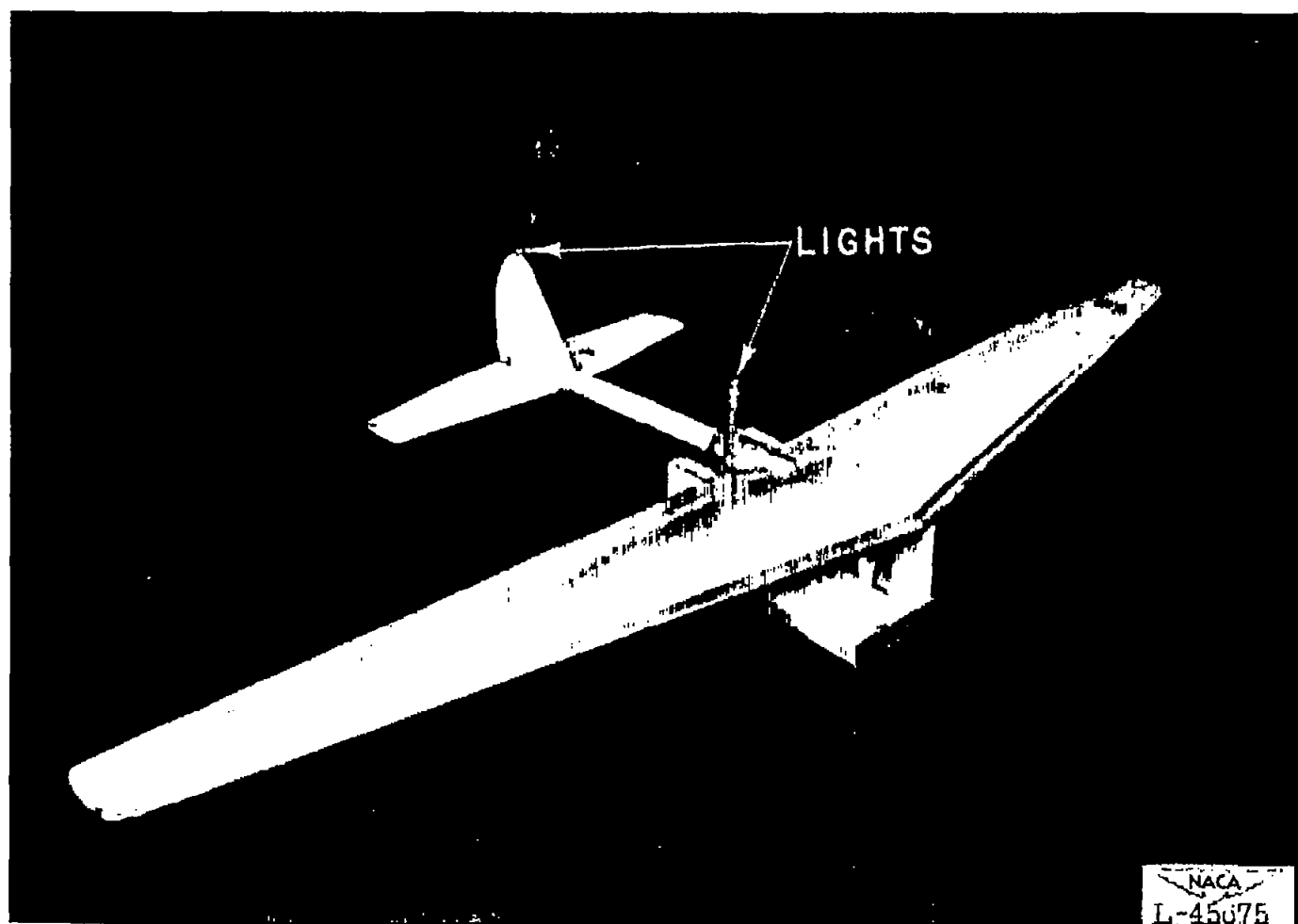


Figure 1.- Model used for tests.



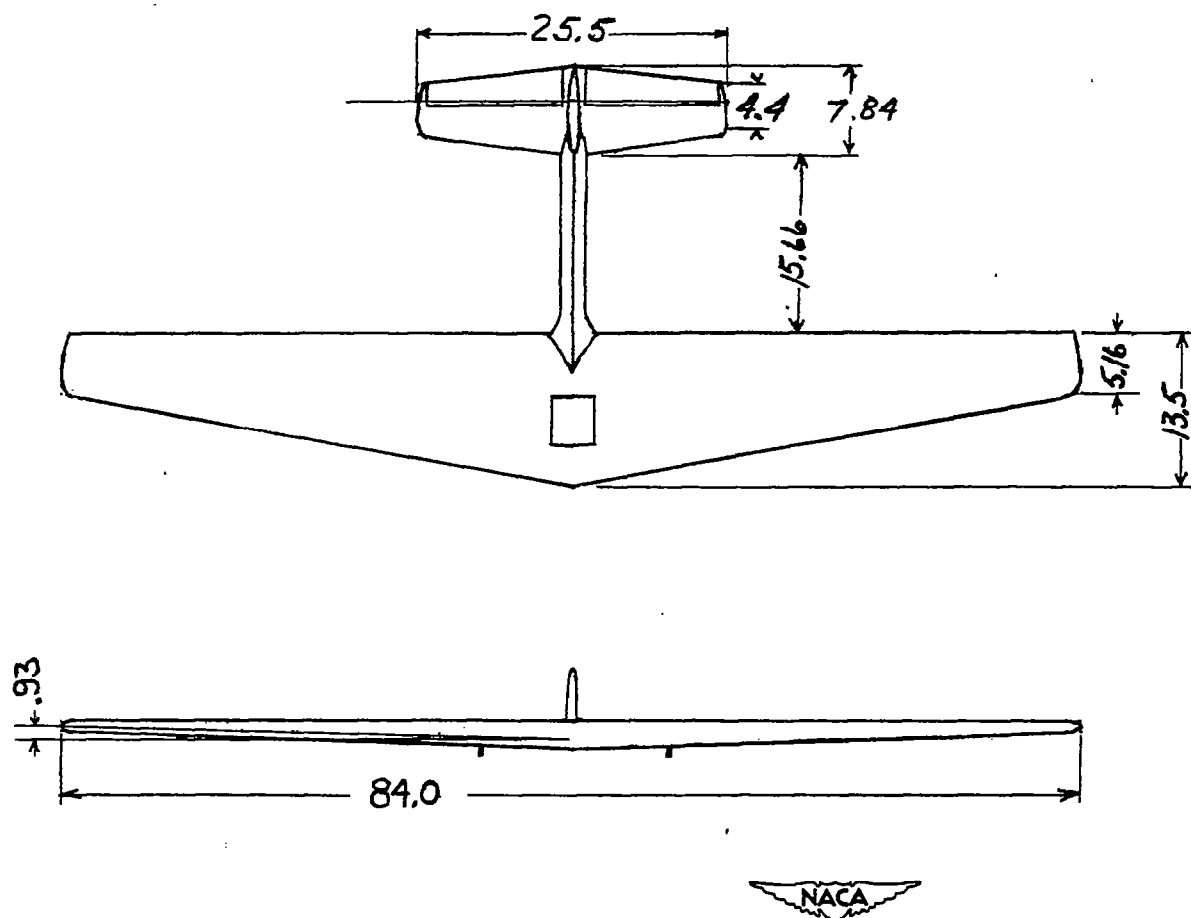


Figure 2.- Line drawing of model.

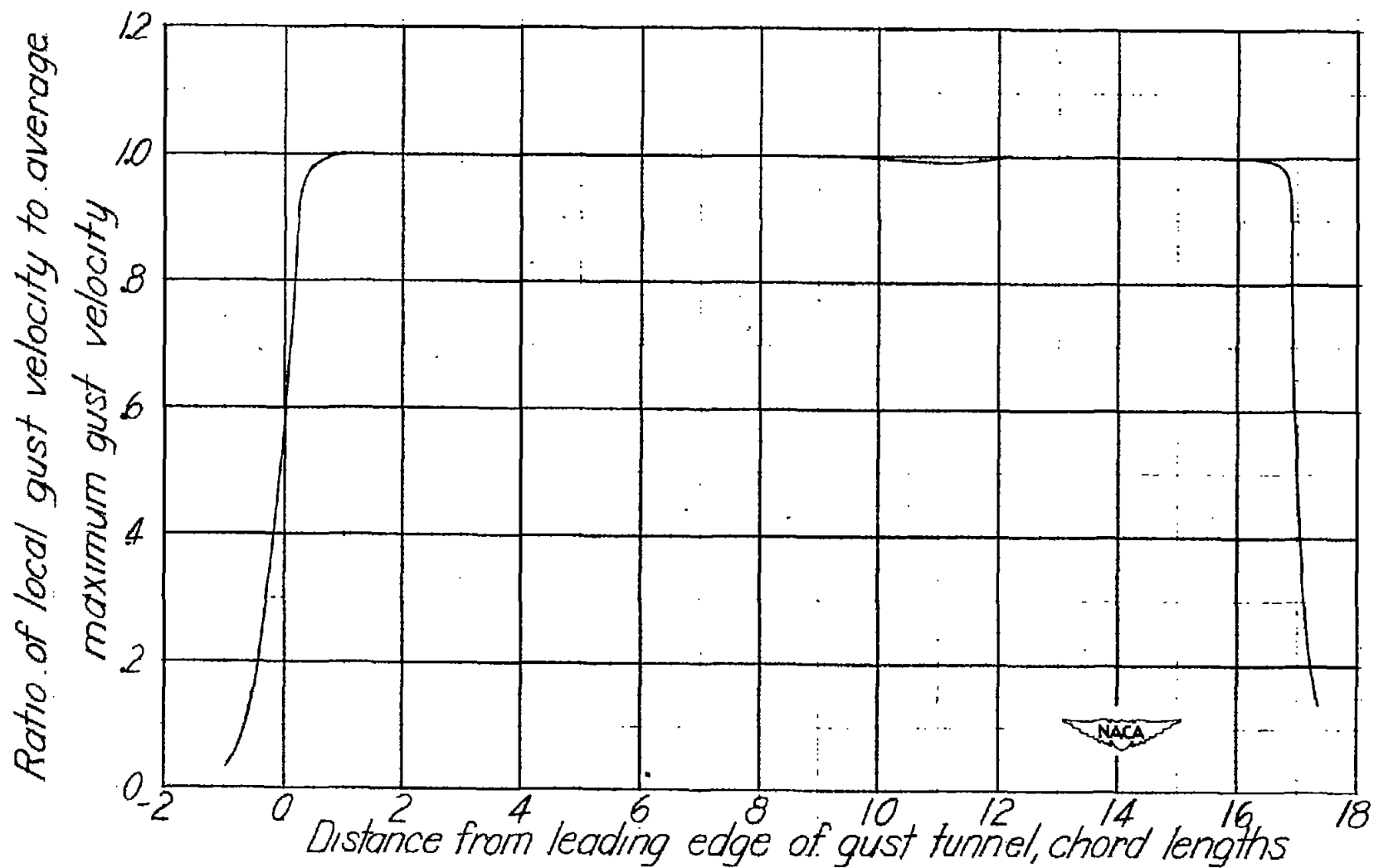


Figure 3.- Velocity distribution of sharp-edge gust measured along center line of gust tunnel.